



DEVELOPMENT OF FLAT PLATE OSCILLATING HEAT PIPE AS A HEAT TRANSFER DEVICE

Kamlesh K Mehta^{a*}, Nirvesh S Mehta^b

^a Gujarat Technological University, Ahmedabad, Gujarat, 382424, India

^b LDRP-ITR, Gandhinagar, Gujarat, 382015, India

ABSTRACT

Heat transfer management is present issue which is progressively increasing importance in line with technology. Effective thermal management is needed to serve to the present trends of power & flux level of upcoming micro devices. This article describes the development of flat plate oscillating heat pipe (FP-OHP) as new entry in the family of two phase heat transfer system. As a unique heat transfer device, flat plate oscillating heat pipe has been considered have a smart prospect due to its advantages: simple fabrication methods & structure, low cost & outstanding heat transfer capability. The development of FP-OHP application is founded on the basis of experimental and theoretical research on two phase heat transfer in FP-OHP. With substantial expectation of FP-OHP application in the coming years, this article attempts to review the development of FP-OHP products. Simultaneously, some favorable and innovative applications of FP-OHP are also studied. This article is predicted to provide fundamental reference for future researcher.

Keywords: flat plate oscillating heat pipe, thermal management, two phase heat transfer

1. INTRODUCTION

As modern systems become smaller and more densely packed, the demands for effective heat transfer devices increases. All new design coming up in field is with higher power dissipation levels. In addition, total power is not the only problem; power per unit area (heat density) is growing in to it. As shown in Fig. 1, Moore's law suggested that the semiconductor transistor level and hence the performance double every 18 months. These advancements are directly related to the power dissipation. Due to more access to computers, consumer electronics, internet and telecommunication power dissipation management has become a challenge.

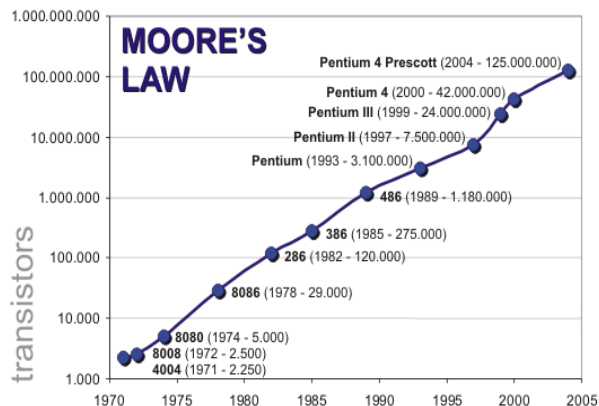


Fig. 1 Transistors level as per Moore's Law

To answers the future issues and projections, technological development is likely to be the only savior.

Heat pipes are very favorable technology for achieving effective heat removal rates and uniform temperature on systems. True evolution of traditional heat pipes began in the 1960; since then, different structures, wicks and working fluids have been used (Faghri, 1995). In the last 25 years, new types of heat pipe such as loop heat pipes were introduced to separate the liquids and vapour flow to increase heat removal rates. Akachi (1990) developed a unique type of heat pipe known as oscillating heat pipe.

This paper attempts to review the operation of oscillating heat pipes, studied the research and development of mainly FP-OHP as heat transfer device. A typical OHP is a small capillary tube which is bent into many turns with partially filled with working fluid as seen in Fig. 2. The ends of the tube may be connected to each other in closed loop, or welded shut in an open loop as seen in Fig. 2a & 2b. The unique characteristic of oscillating heat pipe is that there is no wick structure to return the condensate to the heating source thus there is no countercurrent flow between the liquid and vapour. Heat load is applied to one end of the heat pipe which is known as heat source, the working fluid is vaporize and vapour pressure is increases, so that liquid slugs and vapour plugs are formed. This vapour plugs exert force to liquid slugs towards the heat sink which at the low temperature. In the heat sink side cooling of the vapour bubbles results in reduction of the vapour pressure and the condensation of vapour plugs.

The process of increasing size and reducing size of bubbles in the heat source and heat sink results in an oscillating flow within tube. The heat transfer takes through the sensible heat in liquid slug and through latent heat in the vapour plug. It is generally confirmed by researchers that closed loop OHP has better heat transfer performance (Kim *et al.*, 2003; Zhang *et al.*, 2004). For this reason, most investigation work is done with closed loop OHPs.

*Corresponding author, Email: kamleshnit1@yahoo.com

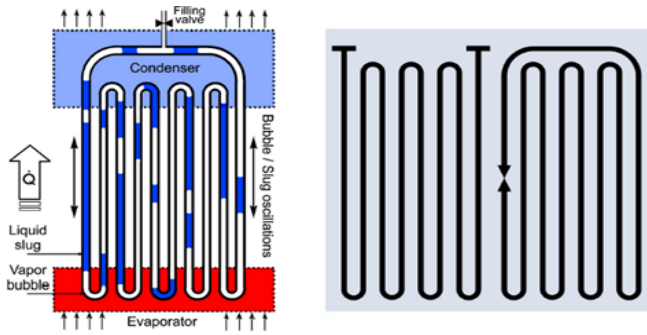


Fig. 2 (a) Schematic of a typical OHP (b) Open OHP (c) Closed OHP

Oscillating heat pipe exists as a continuous copper capillary tube arranged in a serpentine manner, namely tubular oscillating heat pipe (T-OHP) as shown in Fig. 3(a). In recent time, the flat plate oscillating heat pipe (FP-OHP) (Zhang *et al.*, 2008; Borgenmeyer *et al.*, 2007; Thomson *et al.*, 2010; Thomson *et al.* 2009) is developed to overcome the limitations of the T-OHP (i.e. complicated combination of T-OHP, low heat dissipation in space) Fig. 3 (b).

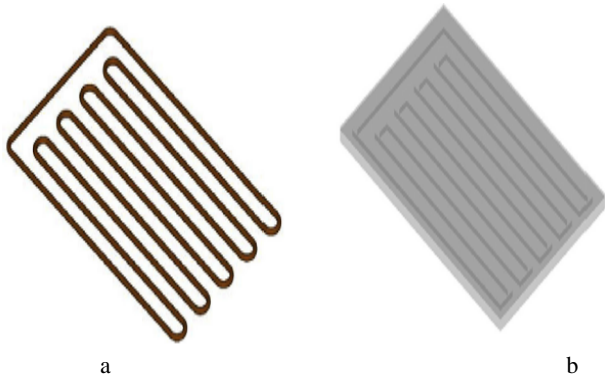


Fig. 3 OHP configuration (a) Tubular OHP; (b) Flat plate OHP

2. OPERATION OF OSCILLATING HEAT PIPE

Heat supplied and rejection and the growth and extinction of vapor bubbles drive the flow in OHPs. Groll *et al.* (2003) studied using a pressure-enthalpy diagram as shown in Fig. 4. Point A on the P-H diagram is the heat source or evaporator inlet and the process required to get to point B on the diagram can be understood to heat input at a constant pressure due to bubble expansion.

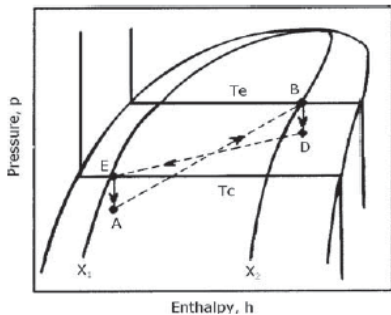


Fig. 4 Thermodynamics of OHP

In adiabatic section from evaporator to the condenser, pressure reduces isenthalpically. The basic thermodynamic process between the condenser's inlet and outlet are complicated, but can be understood to constant pressure heat rejection.

2.1 Merits of Cooling With Oscillating Heat Pipe

Fig. 5 shows a comparison between the cooling by a solid metal and OHP for explaining the advantages of OHP. In the longitudinal direction of an oscillating heat pipe the temperature gradient can be much smaller than that of in a solid metal.

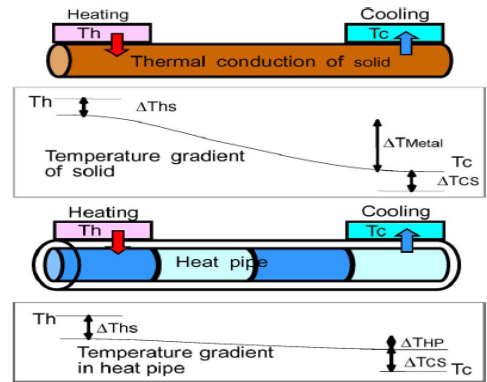


Fig. 5 Comparison between the cooling by OHP and by solid metal

Also, there is less time delay of heat transfer in a heat pipe because of oscillating flow of working fluid, which is different from the solid metal. The effective thermal diffusivity and quick response enable oscillating heat pipe to make early detection of local temperature (Natsume *et al.*, 2013).

3. FLUID DYNAMICS IN OSCILLATING HEAT PIPE

Fluid flow in OHP consists of liquid slugs and vapor plugs moving in heat pipe. The liquid slugs in the heat pipe are able to bridge the OHP because surface tension forces are more than gravitational forces. The liquid slugs and vapor plugs distribute themselves in the partially filled OHP. There is a curved upper surface of a liquid in a tube on either side of each vapor slug caused by surface tension. The control volume for one liquid slug in an OHP and forces acting on it shown in Fig. 6. Shafii *et al.* (2001, 2002) described the motion of *i*th liquid slug within the OHP with an inner diameter of *D* and area of *A* by the momentum equation given by:

$$\frac{dm_{li} v_{li}}{dt} = [p_{vi} - p_{v(i+1)}]A - \pi D L_{li} \tau$$

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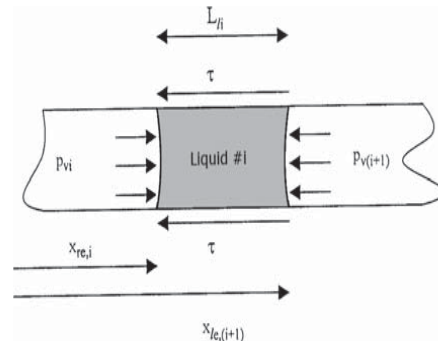


Fig. 6 Liquid slug in an OHP

Where, m_{li} , v_{li} and L_{li} are the mass, velocity and length of the *i*th liquid slug, respectively. $[p_{vi} - p_{v(i+1)}]$ are the driving forces for the oscillatory flow in OHP. The shear stress τ value depends on the whether the liquid flow is turbulent or laminar.

4. FLUID PARAMETERS AFFECTING FP-OHP PERFORMANCE

The physical parameters that affect FP-OHP performance are numerous and include the following.

4.1 Maximum radius of channel in FP-OHP

The radius of channel must be small enough that surface tension forces overcome gravitational forces and so that liquid slugs and vapor plugs can develop in the FP-OHP. When channel radius becomes smaller, the surface tension will dominate liquid-vapor interface. The maximum radius of channel in FP-OHP is characterized by the Bond number, i.e.

$$Bo = \frac{g(\rho_l - \rho_v)r_h^2}{\sigma}$$

where, Bo is the bond number, $(\rho_l - \rho_v)$ is the density difference between the two phases, g is gravitational force, σ is the surface tension and r_h is the hydraulic radius of the channel. A high bond number indicates that heat pipe is relatively unaffected by the surface tension. A low number shows that the surface tension dominates. Rearranging Eq. (2), the maximum hydraulic radius for an FP-OHP can be described as;

$$r_{h,max} \leq \sqrt{\frac{\sigma Bo}{g(\rho_l - \rho_v)}}$$

Cai *et al.* (2006) suggested that for effective flow in an oscillating heat pipe, the bond number should be equal to 2 (Groll *et al.*, 2004).

4.2 Heat Flux Level

The oscillating flow of working fluid becomes vigorous resulting in higher heat transport capability, when the power input increases. The heat transport capability of heat pipe is directly related to channel density (channel/unit volume) (Charoensawan *et al.*,2008; Sarangi *et al.*,2013). The flat plate oscillating heat pipe can increase the channel density so that increases the thermal performance of the heat pipe at higher heat flux level. Also input heat flux is important parameter for the FP-OHP. The experimental results suggested that there existed a minimum heat flux to make the FP-OHP start to operate and this minimum heat flux is called startup heat flux of the FP-OHP. The heat flux has a relationship with oscillation motion of liquid slugs and vapor plugs, as well as heat transfer in FP-OHP. The heat flux also affected the sensible heat to the latent heat during the heat transfer in the heat pipe. The sensible heat will dominate the heat transfer, when heat flux is very low and the latent heat overcomes the sensible heat, when the heat flux is becomes higher. Researcher (Lin *et al.*,2008; Li *et al.*,2008) observed that the thermal resistance of the heat pipe decrease with increasing of the heat flux. Hu *et al.* studied that the startup time was related with heat flux level.

4.3 Number of channels in the FP-OHP

The number of channels significantly influences the internal pressure and thermal performance of the FP-OHP. Quan *et al.* (2009) observed that the increasing the number of channel could improve the internal pressure distribution and gives better heat transfer characteristics. Yang *et al.* (2008) investigated a oscillating heat pipe consisted of 40 parallel channels, it was found that the OHP operated successfully with all inclination angles. Charoensawan *et al.* (2003) pointed out that the critical number of channels of the OHP was influenced by the properties of working fluids and the radius of channels. It was found by

the above mentioned experimental researches that increasing the numbers of channels would be helpful to strengthen the internal pressure distribution and weaken the influence of the gravity.

4.3 Physical Properties of working fluid

The physical properties of the working fluid, such as the latent heat, surface tension, specific heat, viscosity, thermal conductivity etc., have intense effects on the thermal performance of FP-OHP. Out of the number of methods to increase the heat transfer performance of FP-OHP, the most direct and efficient one is to select proper fluid as a working fluid.

Latent heat: A low latent heat will be advantageous to help the bubbles generating more quickly, as well as reduce the startup time of the heat pipe. So it is suggested that when the heat load is very low, the working fluid with low latent heat is desirable. Also, when the heat load is very high, the latent heat becomes the main part of the heat transfer process, so that working fluid with higher latent heat can transfer more heat from the heat source.

Surface tension: Higher surface tension will increase the allowable radius of the channel and also the pressure drop in the heat pipe. On the other hand, the capillary resistance is related to the surface tension. As a result the working fluid with higher surface tension has more capillary resistance (Taft *et al.*,2011). According to Eq. (1),the working fluid with higher surface tension will increase the radius of channel of the FP-OHP and relative increase the thermal performance of the heat pipe because of reduction in friction resistance when radius of channel is larger.

Specific heat: A high value specific heat will increase the portion of the sensible heat transfer in heat pipe. When the heat load to the heat source is very low, the main heat transfer is by the sensible heat. Because of this reason, fluid with higher specific heat is desirable.

Viscosity: It is easy to understand that the working with lower dynamic viscosity will decrease the shear stresses in the heat pipe and reduce the pressure drop. This will decrease the required heat load in heat source to start the oscillation of working fluid (Xiao *et al.*,2012).

Thermal conductivity: A higher value of thermal conductivity increases the heat transfer in FP-OHP. Furthermore, it can also reduce the temperature difference between the heat source and heat sink. The effects of thermal conductivity related to temperature distributions and also response time of the heat pipe.

Experimental investigations were carried out to know the thermal performance of the OHP with different working fluids. Wang *et al.*(2005) observed that the OHP charged with water gives better heat transfer performance than R141b and ethanol. Charoensawan *et al.* (2003) indicated that when the inclination angle of OHP was 90°, the OHP with water showed a better performance when compared to ethanol and R123. Qu *et al.* (2011) studied performance of the micro-OHP .The results indicated that R113 was suitable at low heat load, while FC-72 was more favorable when heat load was relatively high. Also, Qu *et al.* (2009) observed the heat transfer characteristics of the OHP when heat pipe charged with methanol, water and acetone, respectively. The results indicated that the acetone was the best choice among them when heat load is low. Recently, nanofluids as working fluid in a heat transfer device is one of the main research topics in heat transfer area due to their properties. Nanofluids have been used to increase heat transfer performance of the OHP. Qu *et al.* (2008) presented that when the nanofluid was used, OHP could startup quickly at low heat load. Lin *et al.* (2008) compared the performance of the Ag/H₂O nanofluid and water. It was observed that the thermal resistance of OHP was decreased significantly when the working fluid was silver nanofluid.

4.4 Inclination Angle

The research methods utilized to investigate the performance of the heat pipe by changing its inclination angle. Vassilev *et al.* (2007) observed the influence of inclination angle using a FP-OHP. It was found that the

thermal resistance of the FP-OHP slightly increased with increased with the inclination angle (0° - 90°). Xiao *et al.* (2007) studied that the best performance was obtained when inclination angle of heat pipe was 60° . Thompson *et al.* (2011) investigated the miniature three dimensional FP-OHP. The results indicated that while the inclination angle was 90° , the FP-OHP could dissipate heat flux up to 20 W/cm^2 and kept temperature of heat source below 100°C . Meanwhile, the effects of the inclination angle also related with other parameters, such as the working fluid and radius of channel.

4.5 Charge Ratio

The charge ratio of the FP-OHP is defined as the ratio of working fluid volume to the total volume of the FP-OHP. The charge ratio has significant effects on the performance of FP-OHP. If the charge ratio is too low, there is not enough working fluid to start oscillating flow and evaporator may dry out. If the charge ratio is too high, there will not be enough vapor bubbles to force the liquid slugs, and the heat pipe will act as a thermosyphone. Experimental results indicated that the charge ratio is between 20% and 80%, the FP-OHP can operate [Shafii *et al.*, 2001]. Some researchers have studied the optimum charge ratio. Yang *et al.* (2008) observed that the charge ratio of 50% was optimum to obtain the better performance. Liu *et al.* (2013) investigated the oscillating heat pipe with ethanol as working fluid. It was found that the optimum range of charge ratio was 41% -52%. Qu *et al.* (2009) investigated the effects of charge ration on FP-OHP. The results showed that for FP-OHP with FC-72 and acetone, the optimum charge ratios were 67% and 36%. Qu *et al.* (2009) investigated that the optimum charge ratios were 55% for FC-72 and 41% for R113. The optimum charge ratios observed by above researchers for the FP-OHP operated in tested situation. It seems that the optimum charge ratio of FP-OHP varies with different parameters, such as the inclination angle, the working fluid and the heat load.

5. Development of FP-OHP as heat Transfer Device

The FP OHP is developed in different shape and size depends on its application. An OHP is heat exchanger is developed as shown in Fig. 7 in range from $30 \text{ mm} \times 30 \text{ mm}$ with a total length up to 2.0 m Fig. 8 (Ma., 2015). FP OHP is fabricated for heat spreader Fig. 3 in flat shape and U shaped for battery cooling Fig. 10. Due to significance reduction in the temperature difference between heat source and heat sink and excellent manufacturing consideration, the use of FP-OHPs results in substantial decrease in weight because two phase heat transfer in FP-OHPs. The manufacturing cost for FP OHP products shown in Fig. 10 is close to the raw material.

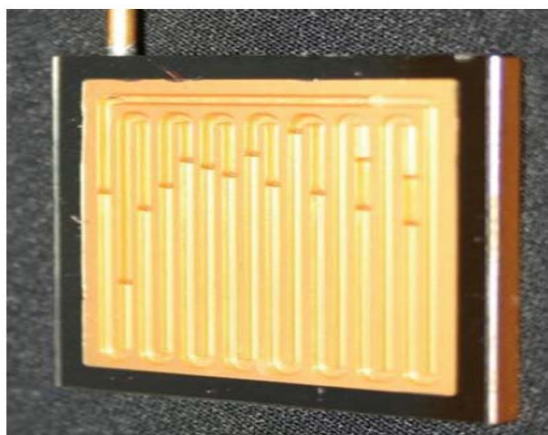


Fig. 7 OHP Photo $3 \text{ mm} \times 3 \text{ mm}$ silicon carbide



Fig. 8 FP-OHP 8-ft long



Fig. 9 Aluminum FP-OHP $12 \text{ mm} \times 12 \text{ mm}$

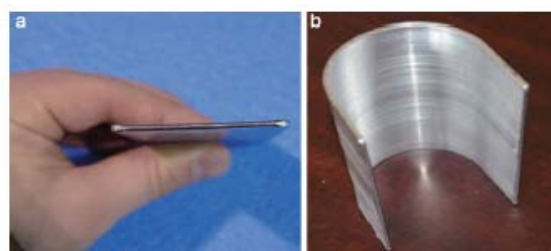


Fig. 10 FP OHP for battery cooling (a) Flat plate shape (b) U shaped plate

Thompson *et al.* (2010) developed FP OHPs embedded with two layers of channel configuration as shown in Fig. 11. The channel configuration had dimensions of $0.762 \text{ mm} \times 0.762 \text{ mm}$. Both layers of the FP OHP had 15 turns and two ends were interconnected to form a closed loop. It was found that the FP-OHP embedded with two layers of channel configuration can substantially increase the heat transport capability.

Borgmeyer *et al.* (2007) investigated FP OHP covered with a lexan sheet as shown in Fig. 12. The FP OHP channel configuration was made using a carbide end mill with dimensions of $1.59 \text{ mm} \times 1.59 \text{ mm}$ in a square shape. This design represents the actual movement of liquid in a FP-OHP by using transparent cover. The thickness of FP-OHP is 2.54 mm and its area $76.2 \text{ mm} \times 76.2 \text{ mm}$. The FP-OHP had two separate closed loops to reduce the length of each channel so that pressure drop from heat source to heat sink could also be reduced.

Boswell *et al.* (2015) investigated light weight heat sink embedded with the FP OHP for thermal management of military (CCA) circuit card assemblies as shown in Fig. 13. These FP OHP heat sinks efficiently transfer heat generated by circuit card assemblies to the assembly's edges.

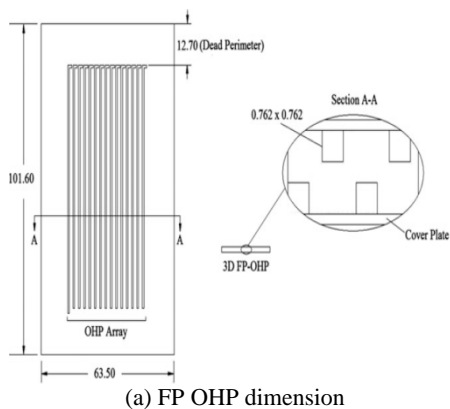


Fig. 11 FP OHP embeded with two layes of channel configuration

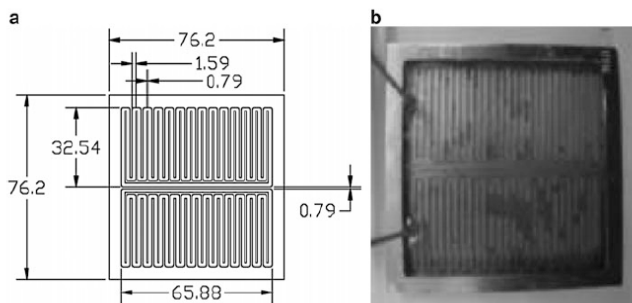


Fig. 12 A FP-OHP (a) schematic (b) photo of developed FP-OHP

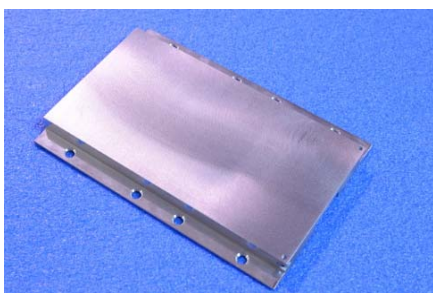


Fig. 13 FP OHP heat sink military circuit card assembly



Fig. 14 FP OHP Air cooled microchip heat sink



Fig. 15 FP OHP heat spreader

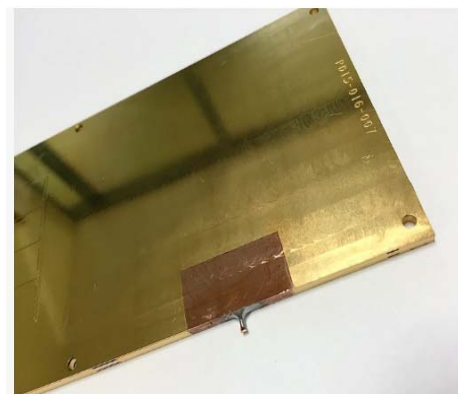


Fig. 16 FP OHP heat sprader with gold plating

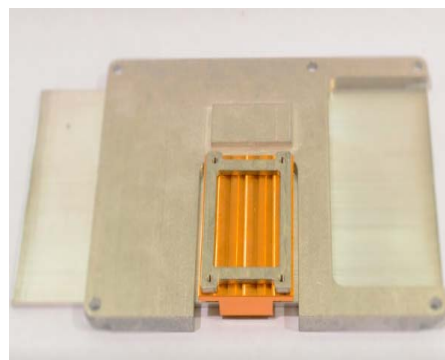


Fig. 17 FP OHP thermal module for military chipset

Thermavant technologies began researching the application of FP-OHP as a result of an air cooled microchip heat sink (Fig. 14), reliable and high conductivity heat spreaders (Fig. 15). Thermavant investigated the improved heat transfer properties of different materials (Fig. 16). FP-OHP chip carriers (Fig. 17) and heat spreaders (Fig. 18) will be used to transfer heat dissipated by micro-chips to the spacecrafts. Thermavant demonstrated the thermal performance of different manufacturing methods for making FP-OHP heat spreaders.

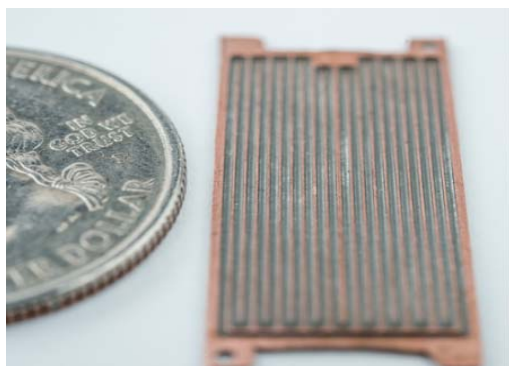


Fig. 18 FP OHP heat spreader for RF device

This section has demonstrated actual applications of FP-OHPs in the area of heat spreader, heat sink, electronic cooling, etc. The above developments indicate that the FP-OHP has a wide application prospects in these fields. Meanwhile, some of the applications are in initial stage, systemic investigations are still needed before the actual commercial applications.

6. CONCLUSIONS

As a new entry of heat transfer device, the FP-OHP has very good application in future. The unique advantages including no weak structure, low cost, easy manufacturing methods, make it one of the new research topics in the field of thermal management. The performance of FP-OHP is greatly influenced by various parameters, such as radius of channel, heat flux, inclination angle, charge ratio, and many investigators have been conducted to study the heat transfer characteristics of FP-OHP. Flat plate oscillating heat pipe has been applied with various devices to increase the heat transfer performance of the system. With the great expectation for the FP-OHP application in the future, it is worth pursuing in future research on flat plate oscillating heat pipe.

NOMENCLATURE

C	heat capacity ($J/m^3 \cdot K$)
c_p	specific heat ($J/kg \cdot K$)
h	latent heat of phase change (J/kg)
k	thermal conductivity ($W/m \cdot K$)
M	molar mass ($kg/kmol$)
q''	heat flux (W/m^2)
R	reflectivity
R_g	specific gas constant ($J/kg \cdot K$)
t	time (s)
T	temperature (K)
u	interfacial velocity (m/s)
x	coordinate (m)

Greek Symbols

δ	optical penetration depth (m)
ϵ	total emissivity
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant ($W/m^2 \cdot K^4$)

Superscripts

0	last time step
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Subscripts

0	initial condition
e	electron
l	lattice
∞	ambient environment

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